

# GRB 130603B: No Compelling Evidence For Neutron Star Merger

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## ABSTRACT

Near infrared (NIR) flare/rebrightening in the afterglow of the short hard gamma ray burst (SHB) 130603B measured with the Hubble Space Telescope (HST) and an alleged late-time X-ray excess were interpreted as possible evidence of a neutron-star merger origin of this SHB. However, the X-ray afterglow that was measured with the Swift-XRT and Newton XMM have the canonical behaviour of a synchrotron afterglow produced by a highly relativistic jet. The H-band flux observed with HST 9.41 days after burst is that expected from the measured late-time X-ray afterglow. A late-time flare/re-brightening of a NIR-Optical afterglow of SHB can be produced by jet collision with an interstellar density bump, or by a kilonova, but jet plus kilonova can be produced also by the collapse of compact stars (neutron star, strange star, or quark star) to a more compact object due to cooling, loss of angular momentum, or mass accretion.

*Subject headings:* gamma-ray bursts, supernovae: general

## 1. Introduction

Stripped envelope supernova explosions and neutron star mergers in close binaries were originally suggested by Goodman, Dar and Nussinov (1987) as possible sources of cosmological gamma ray bursts. However, their proposed underlying mechanism - a spherical fireball produced by neutrino-antineutrino annihilation into electron positron pairs beyond the surface of the collapsing/merging star- turned out not to be powerful enough to produce GRBs observable at very large cosmological distances. Consequently, Shaviv and Dar (1995) proposed that highly relativistic jets of ordinary matter are probably ejected in such events, and produce narrowly collimated GRBs by inverse Compton scattering of circumstellar light. They also suggested that short GRBs may also be produced by highly relativistic jets ejected in the phase transition of compact stars, such as neutron stars, strange stars and quark stars, into more compact objects due to mass accretion or to cooling and loss of angular momentum via winds and radiation. After the discovery of GRB afterglows, Dar (1998) proposed

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that they are highly beamed synchrotron radiation produced in the collision of these highly relativistic jets with the interstellar matter.

By now, there is convincing evidence that long duration GRBs are produced mostly by highly relativistic jets launched in stripped envelope supernova explosions (mainly of type Ic), but, despite enormous observational efforts, the origin of short duration GRBs remains unknown. In fact, the circumstantial evidence that has been claimed to link short hard GRBs (SHBs) with neutron star mergers in close binaries, such as their location in both spiral and elliptical galaxies and the distribution of their location offsets relative to the center of their host galaxies, which extend to a distance of 100 kpc (e.g., Berger et al. 2013 and references therein) and beyond? (e.g., SHB 080503 with the lack of a coincident host galaxy down to 28.5 mag in deep Hubble Space Telescope imaging, Perley et al. 2009) actually favours single compact stars with large natal kick velocity as progenitors of SHBs (Dado, Dar and De Rújula 2009a) over neutron star binaries, which have much lower Galactic velocities.

It was predicted that neutron star mergers create significant quantities of neutron-rich radioactive nuclei whose decay should result in a faint transient in the days following the burst, a so-called kilonova or macronova (Li and Paczynski 1998). Recently, the broad band afterglow of the SHB 130603B (Melandri et al. 2013; Golenetskii et al. 2013) that was measured with the Swift X-ray telescope (XRT), Newton XMM, HST and ground based optical and radio telescopes was interpreted as possible evidence of a neutron-star merger origin of SHB 130603B (Tanvir et al. 2013a,b; Berger et al. 2013; Fong et al. 2013). However, in this letter we show that the X-ray afterglow of SHB 130603B, which was measured with Swift XRT (Swift/XRT GRB light-curve repository, Evans et al. 2009) and Newton XMM (Fong et al. 2013) has the canonical behaviour of a synchrotron afterglow produced by a highly relativistic jet propagating in a normal interstellar environment, as predicted by the cannonball model of GRBs (Dado, Dar and De Rújula 2002, 2009a,b; Dado and Dar 2013) long before its empirical discovery (Nousek et al. 2006). This canonical X-ray afterglow does not have a "mysterious late-time X-ray excess" as claimed in Fong et al. 2013, and the flux observed in the NIR H-band with HST 9.6 days after burst (Tanvir et al. 2013a,b) is that expected from the measured late-time X-ray afterglow.

Moreover, a fast decline of a late-time afterglow followed by a re-brightening/flare in the NIR and optical afterglow of a GRB can be produced by a jet colliding with a density bump in the interstellar medium (e.g., Dado, Dar and De Rújula 2002, 2009b), as was observed in several long-duration GRBs, such as 030329 (Lipkin et al. 2004; Matheson et al. 2003) 070311 (Guidorzi et al. 2007) and SHBs such as 050724 (Malesani et al. 2007) and 080503 (Perley et al. 2009). The host galaxy of SHB 130603B at redshift  $z = 0.356$  (Thone et al. 2013), as seen in high-resolution HST imaging (Tanvir et al. 2013b), is a perturbed

spiral galaxy due to interaction with another galaxy. SHB 130603B was located in a tidally disrupted arm. The interaction of the SHB jet with such a bumpy environment may have caused the flare/re-brightening in the NIR afterglow observed with the HST on day 9.41.

Furthermore, a late-time flare/re-brightening of a NIR-Optical afterglow of SHB can be produced by either a jet collision with an interstellar density bump or a kilonova, but jet plus kilonova can be produced also by collapse of compact stars (neutron star, strange star, or quark star) to a more compact object due to cooling, loss of angular momentum, or mass accretion. In fact, single compact stars are more likely to be found at large offsets from galactic center/disks (e.g., in the galactic halos or the intergalactic medium) than neutron star binaries or black hole-neutron star binaries.

## 2. The X-ray afterglow of SHB 130603B

The conclusion of Fong et al. (2013) that the X-ray afterglow of SHB 130603B shows ”a mysterious late-time X-ray excess” was based on a standard fireball model analysis of its X-ray afterglow. The standard fireball model, however, predicts that the temporal index  $\alpha$  of the afterglow of a conical jet that is parametrized as a smoothly broken power-law,  $F_\nu \propto t^{-\alpha} \nu^{-\beta}$ , increases by  $\Delta\alpha_X = 0.75$  across the jet break, independent of the spectral index  $\beta_X$  of the afterglow (Dado and Dar 2013). The temporal indices  $\alpha_X = 0.35 \pm 0.08$  and  $\alpha_X = 1.61 \pm 0.08$  before and after the break, respectively, that were reported for instance in the Swift-XRT GRB Catalogue (Evans et al. 2009) yield  $\Delta\alpha_X = 1.26 \pm 0.11$  ( $\alpha_X = 1.75 \pm 0.08$  for the combined data of Swift-XRT and Newton XMM yield  $\Delta\alpha_X = 1.40 \pm 0.11$ ), which is at odds with the conical fireball model.

In contrast, the X-ray afterglow of SHB 130603B that was measured with Swift-XRT (Swift/XRT light curve repository, Evans et al. 2009) and Newton XMM (Fong et al. 2013) has the canonical behaviour of a normal synchrotron afterglow produced by a highly relativistic jet propagating in a normal interstellar environment of its host galaxy (Dado, Dar and De Rújula 2009a,b). This canonical behaviour of the X-ray afterglow was predicted (Dado, Dar and De Rújula 2002) long before the launch of Swift and its empirical discovery (Nousek et al. 2006). It consists of an early plateau phase that follows the fast decline phase of the prompt emission and breaks smoothly into a late-time ( $t \gg t_b$ ) power-law decline with a power law index that satisfies the cannonball (CB) model closure relation,

$$\alpha_X = \beta_X + 1/2 = \Gamma_X - 1/2, \quad (1)$$

independent of the pre-break power-law index, where  $\Gamma_X$  is the photon spectral index of the X-ray afterglow (see, e.g., Dado and Dar 2013 and references therein). Using the value

$\beta_X = 1.15 \pm 0.11$ , which was obtained by de Ugarte Postigo et al. (2013) from the Swift-XRT data, the CB model closure relation yields  $\alpha_X = 1.65 \pm 0.11$ . This value is consistent within errors with the post break value  $\alpha_X = 1.61 \pm 0.08$  reported for SHB 130603B in the Swift-XRT GRB Catalogue (Evans et al. 2009).

In the CB model, the canonical light-curve of the X-ray afterglow depends only on three parameters (Dado, Dar and De Rújula 2009a): the product  $\gamma\theta$  of the bulk motion Lorentz factor of the jet and the viewing angle relative to the direction of motion of the jet, the jet deceleration parameter  $t_0$ , and the spectral index  $p_e$  of the Fermi accelerated electrons in the jet that satisfies  $p_e = 2\beta_X$ . A CB model fit to the light-curve of the 0.3-10 keV X-ray afterglow of SHB 130603B, which was measured with Swift XRT (Evans et al. 2009) and with Newton XMM assuming the spectral index that was measured by Swift, is shown in Fig. 1. The best fit value  $p_e = 2.37$  yields  $\beta_X = p_e/2 = 1.18$ , which is consistent with the late-time photon index  $\Gamma_X = 2.21 \pm 0.18$  that is reported in the Swift-XRT GRB Catalogue (Evans et al. 2009). The two other best fit parameters,  $\gamma\theta = 0.55$  and  $t_0 = 878$  s, yield a deceleration break (so called "jet break") at  $t_b \approx 1500$  s.

Thus, we conclude that there is no evidence for a "mysterious late-time X-ray excess" that was claimed in Fong et al. 2013, and was explained by a magnetar contribution to the afterglow emission of SHB 130603B (Fong et al. 2013; Metzger and Piro 2013; Fan et al. 2013).

### 3. The near infrared-optical afterglow

The conclusion that the NIR-optical afterglow of SHB 130603B provides possible evidence of a macronova/kilonova was based on a re-brightening of the NIR afterglow observed with the Hubble space telescope (HST) in the H band on day 9.41, which is well above that extrapolated from the fast decline of the optical afterglow in the r band during the first day after the break around 0.3 d (Berger and Fong 2013, Berger et al. 2013, Fong et al. 2013).

However, in the CB model, when the spectral index of the late-time NIR and optical bands is above the spectral break,  $\beta_H \approx \beta_X$  and consequently  $\alpha_H = \beta_H + 1/2 \approx \alpha_X$ . Using the ground-based JK-band observations extrapolated to the H band (Fong et al. 2013) and the HST H-band measurement, we obtained that  $\alpha_H = 1.61 \pm 0.08$  in the time interval 0.61-9.41 d, which is in agreement, within errors, with the power-law index  $\alpha_X = 1.68 \pm 0.08$  of the joint late-time Swift-XRT observations (Evans et al. 2009) and XMM Newton observations (Fong et al. 2013).

Moreover, a broken power-law best fit to the unabsorbed late-time broad band NIR,

Optical and Swift X-ray spectrum by de Ugarte Postigo et al. (2013) yielded  $\beta = 0.65 \pm 0.09$  below a break at  $\nu_b = 9.55 \times 10^{15}$  Hz and  $\beta_X = 1.15 \pm 0.11$ . Using  $\lambda = 12.4\text{\AA}$  for 1 keV photons,  $\lambda = 16300\text{\AA}$  for H-band photons and  $\lambda_{\text{break}} = 314\text{\AA}$ , the expect flux ratio of the H and X-ray bands is  $F_H/F_{\text{keV}} \approx 536 \pm 160$ . This ratio is in good agreement within errors with the observed ratio  $F_H/F_{\text{keV}} = 623 \pm 160$  of the H-band flux measured with HST on day 9.41 after burst and the 1 keV X-ray flux obtained by extrapolating the joint Swift/XRT - Newton XMM 1 keV flux to day 9.41.

The highly relativistic jets of plasmoids (cannonballs) that produce GRBs can encounter a bumpy interstellar medium in the host galaxy. Also, the opacity along the line of sight to the jet in the host can vary significantly due to the "superluminal" motion of the line of sight to the jet in the host galaxy. The collision of a jet with an over-density bump can produce chromatic re-brightening/flare in the NIR-Optical afterglow (e.g., Dado, Dar and De Rújula 2002, 2009b) as was observed in the late-time optical afterglow of several long duration GRBs such as 030329 (Lipkin et al. 2004; Matheson et al. 2003) and SHBs such as 050724 (Malesani et al. 2007) and 080503 (Perley et al. 2009), while under density can cause a fast temporal decline of an afterglow ( $\alpha > 2$ ), as observed in several GRBs (Swift/XRT GRB catalogue, Evans et al. 2009). Such density variations cause spectral and temporal variations in the afterglow, which otherwise has a smooth power-law behaviour. After an over density or an under density, the late-time ( $t \gg t_b$ ) closure relation of the CB model is recovered when the column density as function of distance converges to that of a the mean ISM density. This can explain both a fast decline of the NIR-optical afterglow of SHB 130603B after an over density followed by an under density, and a recovery to the normal power-law decline like that of the X-ray afterglow.

#### 4. The Macronova - SHB association

SHBs may be produced by highly relativistic jets launched in the collapse of compact stars (neutron star, strange star, or quark star) to a more compact object due to loss of angular momentum, cooling, or mass accretion (Dar et al. 1992). During neutron star merger, or collapse of a compact star to a more compact object, the crust layers can be stripped off by very strong outgoing shocks. Neutrino-antineutrino annihilation into electron-positron pairs behind such blown off layers can than produce fireball with a super Eddington luminosity (Goodman, Dar and Nussinov 1987), which can accelerate the blown off crust layers to velocities well above the escape velocity (Paczynski 1990; Dar et al. 1992), although the neutrino luminosity, which is well below the 'neutrino Eddington luminosity', by itself cannot blow off the crust layers:

Balancing the gravitational force with the rate of momentum deposition by neutrinos, and neglecting general relativistic effects, Dar et al. (1992) derived a ‘neutrino Eddington luminosity’ of a compact star

$$L_E(\nu) \approx \frac{4\pi G M m_n c}{\bar{\sigma}} \approx 3.74 \times 10^{54} \frac{M}{M_\odot} \left[ \frac{E_\nu}{15 \text{ MeV}} \right]^2 \text{ erg} \quad (2)$$

where  $G$  is Newton’s gravity constant,  $M$  is the mass of the compact star,  $m_n$  is the mass of a nucleon, and  $\bar{\sigma} \approx 10^{-43} (E_\nu/\text{MeV})^2 \text{ cm}^2$  is the averaged cross section for momentum transfer to a nucleon by charged- and neutral-current scatterings. The gravitational binding energy release in the stellar collapse is transported by neutrino diffusion to the neutrino sphere from where it escapes as a black body neutrino emission with a typical temperature of a few MeV. Such an emission from a neutrino sphere of a compact star of radius  $R \sim 10 \text{ km}$  lasts a few ten seconds or more, during which the neutrino luminosity is well below the neutrino Eddington luminosity of the newly formed compact star.

It is unclear whether a robust r-process occurs in the ejecta, or whether neutrinos drive the composition towards  $^{56}\text{Ni}$  dominated composition (e.g., Surman et al. 2008). All together, the total mass of the ejecta, its composition, density, and velocity, and their radial and angular distributions are highly uncertain, which makes the predicted signal from an associated macronova (Li and Paczynski 1998) very uncertain and unreliable for distinguishing between a single compact star and a binary compact star origin of SHBs.

## 5. Conclusions

Several explanations of the re-brightening of the NIR afterglow of SHB 130603B around 9.41 days after burst have been proposed. These include a macronova/kilonova produced by a neutron star merger in a close binary due to gravitational wave emission (Tanvir et al. 2013b; Fong et al. 2013), an active millisecond magnetar produced in a neutron star merger in close binaries (Metzger and Piro 2013), and a late-time flare produced by collision of the SHB jet with an ISM density bump (Dado, Dar and De Rújula 2002, 2009a).

A jet plus a mini-supernova/macronova/kilonova, however, are not unique to the neutron star merger scenario. They can be produced also in a phase-transition/collapse of compact stars (neutron star, strange star or quark star) to a more compact object due to cooling, loss of angular momentum or mass accretion.

The X-ray afterglow that was measured with the Swift-XRT and Newton XMM has the expected canonical behaviour of a synchrotron afterglow produced by a highly relativistic jet. Its late time behaviour does not support a millisecond magnetar as the power-source

of the chromatic afterglow of SHB 130603B. The late-time H-band flux observed with HST 9.41 days after burst is that expected from an ordinary synchrotron radiation from a jet that produced the measured late-time X-ray afterglow.

Late-time flare/re-brightening of a NIR-Optical afterglow of an SHB can be produced also by jet collision with an interstellar density bump, as seen in several GRBs. The host galaxy of SHB 130603B as seen in high-resolution HST imaging (Tanvir et al. 2013b) is a perturbed spiral galaxy due to interaction with another galaxy. The GRB was located in in a tidally disrupted arm of its host galaxy. The interaction of the GRB jet with such a bumpy environment could produce the flare/re-brightening of the NIR afterglow of the GRB observed with the HST 9.41 days after burst.

The star formation within the host, location of SHB 130603B on top of the tidally disrupted arm, strong absorption features and large line of sight extinction that were observed indicate that the GRB progenitor was probably not far from its birth place (de Ugarte Postigo et al. 2013), untypical to the usually long life time before neutron star merger due to gravitational wave emission in the known neutron star binaries in our galaxy. Moreover, the failure to detect a host galaxy down to 28.5 mag in deep Hubble Space Telescope imaging searches in the case of e.g., SHB 080503 with a late time flare/rebrightening (Perley et al. 2009) suggest a large natal kick velocity of its progenitor, unlikely for compact binaries, but often observed for isolated neutron stars/pulsars (Hobbs et al. 2005).

The true smoking gun for the neutron star merger in close binaries is the detection of gravitational waves. Unfortunately, this is unlikely to occur before the completion of the new generation of gravity-wave detectors, as the sensitivity of current detectors such as LIGO, and Virgo, is several orders of magnitude below what would be required to detect a merger at a distance similar to the nearest SHBs with known redshift.

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## REFERENCES

- Berger, E., Fong, W., Chornock, R. 2013, (arXiv:1306.3960)
- Dado, S. & Dar, A. 2013, A&A 558, A115 (arXiv:1303.2872)
- Dado, S., Dar, A. & De Rújula, A. 2002, A&A, 388, 1079 (astro-ph/0107367)
- Dado, S., Dar A. & De Rújula, A. 2009a, ApJ, 693, 311 (arXiv:0807.1962)
- Dado, S., Dar, A. & De Rújula, A. 2009b, ApJ, 696, 994 (arXiv:0809.4776)

- Dar, A. 1998, *ApJ*, 500, L93 (arXiv:astro-ph/9709231)
- de Ugarte Postigo, A., et al. 2013, arXiv:1308.2984
- Evans, P. A., et al. 2009, *MNRAS*, 397, 1177 (Swift/XRT GRB light-curve repository)
- Fan, Y., et al. 2013, arXiv:1311.7185
- Fong, A., et al. 2013, arXiv:1309.7479
- Guidorzi, C., et al. 2007, *A&A* 474, 793
- Golenetskii, S., et al. 2013, *GCN Circ.* 14771
- Goodman, J., Dar, A. & Nussinov, S. 1987, *ApJ*, 314, L7
- Hobbs, G., et al. 2005, *MNRAS*, 360, 974 (arXiv:astro-ph/0504584)
- Li, L. X. & Paczynski, B. 1998, *ApJ*, 507, L59 (arXiv:astro-ph/9807272)
- Lipkin, Y. M., et al. 2004, *ApJ*, 606, 381
- Malesani, D., et al. 2007, *A&A*, 473, 77
- Matheson, T., et al. *ApJ*, 2003, 599, 394 (arXiv:astro-ph/0307435)
- Melandri, A., et al. 2013, *GCN Circ.* 14735
- Metzger, B. D. & Piro, A. L. 2013, arXiv:1311.1519
- Nousek, J. A., et al. 2006, *ApJ*, 642, 389 (arXiv:astro-ph/0508332)
- Perley, D. A., et al. 2009, *ApJ*, 696, 1871 (arXiv:0811.1044)
- Shaviv, N. J. & Dar, A. 1995, *ApJ*, 447, 863 (arXiv:astro-ph/9407039)
- Surman, R., et al. 2008, *ApJ*, 679, L117
- Tanvir N. R. et al., 2013a, *GCN Circ.* 14893
- Tanvir, N. R., et al. 2013b, *Nature*, 500, 547 (arXiv:1306.4971)
- Thone, C. C. et al., 2013, *GCN Circ.* 14744



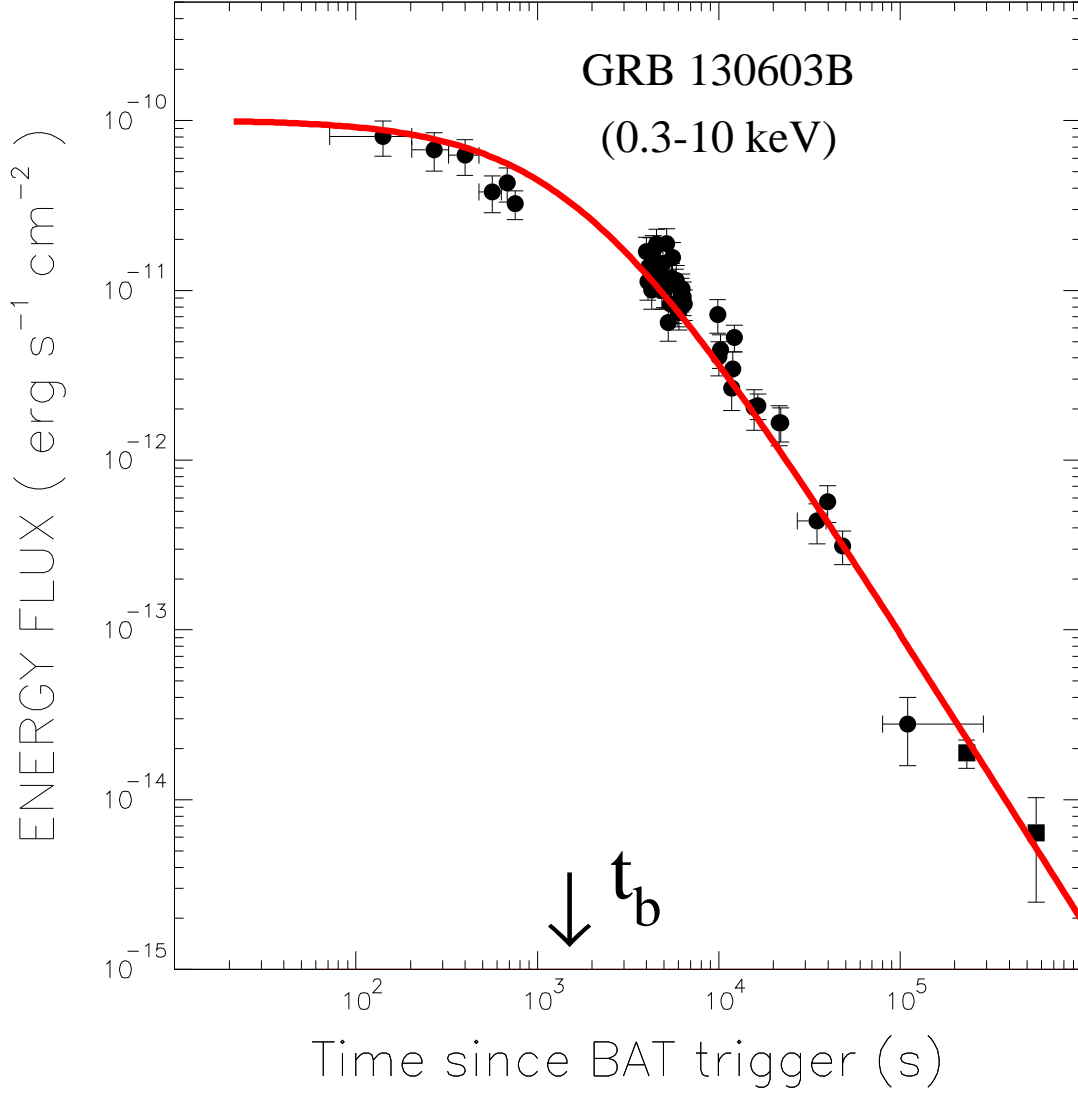


Fig. 1.— Comparison between the light curve of the X-ray afterglow of SHB 130603B, which was measured with Swift XRT (Evans et al. 2009) and with Newton XMM (Fong et al. 2013) assuming the spectral index  $\beta_X = 1.15$  that was measured with Swift, and a CB model fit.